



Protection of AC and DC Microgrids

Challenges, Solutions and Future Trends

Beheshtaein, Siavash; Savaghebi, Mehdi; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.

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Protection of AC and DC Microgrids: Challenges, Solutions and Future Trends

Siavash Beheshtaein, Mehdi Savaghebi, *Member, IEEE* and Josep M. Guerrero, *Fellow, IEEE*
Department of Energy Technology
Aalborg, Denmark
[sib, mes, joz}@et.aau.dk](mailto:{sib,mes,joz}@et.aau.dk)

Abstract— In future, distributed energy resources (RESs) will be utilized at consumption points. As a consequence, power flow and fault current would be bidirectional and topology-dependent; and hence the conventional protection strategies would be inefficient. This paper categorizes the main challenges in AC and DC microgrids, and then investigates the existing and promising solutions for the corresponding challenges. To the authors' knowledge, three parts of smart grids are required to be developed to facilitate implementation of protection scheme in microgrids. The main requirements and open issues of these three parts are discussed at the end of this paper.

Keywords— *Protection, microgrid, AC protection, DC protection, and standards*

I. INTRODUCTION

From the advent of power system in the early 20th century, the structure of power system has undergone a seamless change. Centralized generations have been interconnected to end-consumers through long transmission lines. The existing electricity grid has some deficiencies including high power loss, low penetration of renewable energy sources (RESs), poor visibility, slow response times due to electromechanical devices and lack of standardization and less standardization in the area of automation of power distributions, particularly for RESs, energy storage systems (ESSs) and electric vehicles (EVs). Hence, there is a growing tendency to reconfigure it from the viewpoint of environmental and economic concerns, reliability, security, and efficiency [1]-[4].

The next-generation of electricity grid, so-called “smart grid”, must address the aforementioned shortcomings of the existing grid. The salient features of the promising smart grid in comparison with the existing grid are presented in Tables I [2]-[3]. Communication and data management play an important role in the realization of smart grid; however, there are a number of challenges that have to be addressed in order to have fully robust, secure and reliable smart grid network [5]-[8]. Some of these challenges are an efficient utilization of DERs, utilization of vehicle to grid or grid to vehicle, large scale deployment of technology, smart infrastructure systems

TABLE I. A Comparison of the Existing Grid and the Smart Grid.

Existing Grid	Smart Grid
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

(i.e. information metering, information management, and communication technologies)

A microgrid is defined as a part of the grid consisting of DERs, DS and DL, which could operate autonomously. Microgrids can simplify implementation of many smart Grid functions show in Tables I [2], [9]-[10]. Although microgrids are generally categorized into DC and AC microgrids, hybrid AC/DC microgrid is being considered as a promising topology for the future grid [10]-[12]. The concept of microgrid could be extended to multi-microgrid cluster [10]. This new concept is shown in Fig. 1.

Similar to smart grids, microgrids have encountered a plenty of challenges comprising of energy management, control systems, communication systems, and protection issues. Protection issues in smart grids encompass different entities including reliability analysis, cyber-attacks, protection mechanism, and privacy and security [6], [13]-[14].

This paper divides protection challenges into challenges in AC and DC microgrids. In Section II, protection challenges for AC and DC microgrids are reviewed. In Section III, recent developments and solutions in AC and DC microgrids are discussed. Section IV presents the future trends in protection of microgrids. Finally, Section V presents the conclusions of this paper.

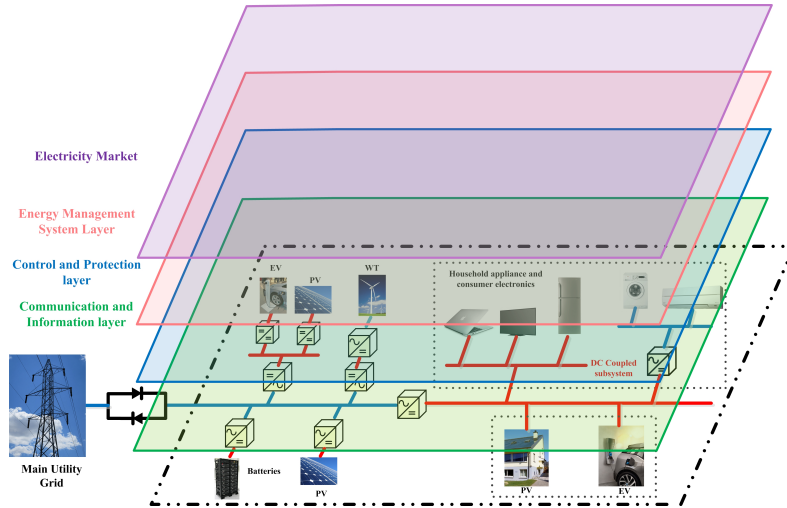


Fig. 1. A typical structure of microgrid.

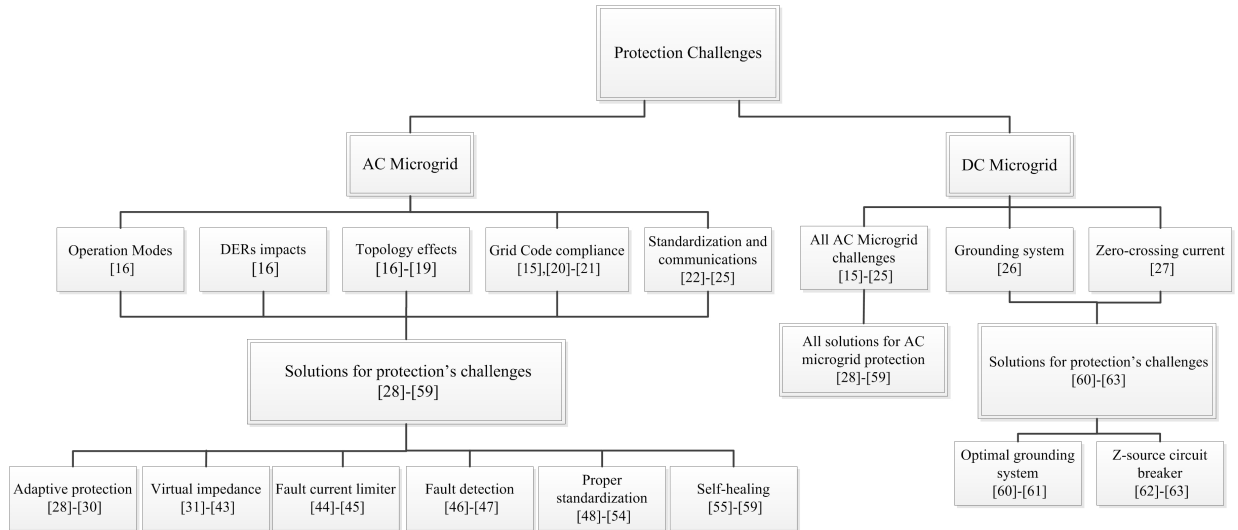


Fig. 2. Challenges and their corresponding solutions for AC and DC microgrids protection.

II. CHALLENGES OF DC AND AC MICROGRIDS PROTECTION

Transition from the conventional grid to the future electric grid arises a set of numerous and new challenges. One of the prominent challenges, which hinder wide adaptation of the microgrid technology, is AC and DC microgrids protection. To meet the basic requirements of the smart grid, i.e. plug and play, and self-healing, a set of new approaches has to be designed to address the smart protection in the microgrids.

A. Technical Challenges in AC Microgrid

The existing grid is centralized generations, long-distance meshed transmission lines and radial distribution network with end-consumers. On the other hand, in the future power system, electronic devices will replace conventional mechanical devices. Furthermore, DERs and DSs are integrated into consumption level. Then, this idea developed to realize

microgrid with features such as plug and play capability, self-healing and resilient to system anomalies. As time goes by, the level of penetration of RESs gets higher. This phenomenon may deteriorate system stability. Thus, the number of modifications in the grid code is needed to ensure the stable operation of the power systems [15]. These considerable changes in the electric energy system leads to a numerous challenges in AC microgrid protection. These challenges are categorized as follows (also see Fig. 2):

- 1) *Microgrid operation modes*: Microgrid operation modes affect on fault currents in term of magnitude and direction. In grid-connected mode, utility and DGs contribute to fault current, while in islanded-mode, fault currents only are fed by DGs. Furthermore, fault current injection capability of DGs are confined to twice their rated current, and lower fault currents result in non-

operation of overcurrent (OC) relays. On the other hand, when microgrid mode changes from grid-connected mode to islanded mode, fault current paths could be different. As a result, sets of settings for microgrid relays are required to cope with the dynamic behavior of DERs in microgrid [16].

- 2) *DERs impacts on PDs*: DERs could affect on PDs coordination in at least two ways [16]:

1. Misoperation of PD at point of common coupling (PCC), due to high current contribution of DER.

2. Sympathetic tripping of PD of DER, when DER is at the adjacent feeder.

Hence, DER locations and fault currents would determine precise relay settings.

- 3) *Microgrid topology effects on PDs coordination*: Microgrids have dynamic topologies. The reasons for that dynamic structures are as follows [17]:

- New DG or load deployments.
- Islanding of the system.
- Fault conditions.
- Reconfiguration of the structure for reasons such as maintenance.

Reconfiguration is a process to modify the microgrid's topological structure by changing the status (open/close) of the circuit breakers or switches, load and generation shedding, and other control actions to redirect power flow to the remaining connected loads [18], [19]. A reconfiguration is vital particularly when microgrid change its operation mode from grid-connected to islanded. Regardless of the reasons behind microgrid topology changes, this phenomenon could impact on current directions and magnitudes, and would lead to miscoordination of PDs.

- 4) *Grid code compliance*: High penetration levels of renewable energy sources in power system has led to elaboration of specific technical requirements in the grid codes. The goal of modification in the existing grid codes is to improve stability of the grid [15]. One requirement of connecting a wind power plant to an electric network is its low voltage ride through (LVRT) capability, i.e., the ability of a power plant to remain connected to a grid during voltage sags and to actively contribute stability to a power system by providing reactive power until fault clearance. Injection of reactive power during the grid fault may jeopardize coordination of the protective relays [20]. In addition, DG units have to take into account the grid code requirements for protective relays coordination [21].

- 5) *Standardization and communication*: The future power distribution grid consists of a considerable number of Intelligent Electronic Devices (IEDs) to cope with a high degree complexity of the future grid. As a result, developing communication, control system as well as standardization of architecture are at a higher priority than grid components.

Communication is increasingly becoming a tool for improving performance of control and protection schemes, particularly when they are applying in microgrids. The applicable standards will emerge to help plug-and-play integration of various smart grid system components. Examples of such standards are IEC 61850, which is a complete standard defining how to describe the devices in an electrical substation (data modeling) and how to exchange the information (communication protocol), for substation automation and ANSI C12.22 for smart metering. Furthermore, power industry is gradually adopting the new technologies to develop the required standards. These technologies include local area network (LAN) to identify the logical network between distributed substation and customers' premises; home area network (HAN) to identify the network of communicating loads, sensors, and appliances beyond the smart meter and within the customer's premises; and finally wide area network to identify the network of upstream utility assets involving power plants, distributed storage, substation and so on. The IEC 61499 standard specifically developed to model and design distributed control [22]. As IEC 61850 logical nodes (LNs) are only defined for describing characteristics of objects and function, standard, the existing of the IEC 61499 standard is essential to define the functionality of IEC 61850 LNs [23]. Recently, integration of IEC 61850 and IEC 61499 was proposed as a promising approach for automation [23]-[25].

Although, ANSI C12.22 and IEC 61850 standards are respectively developing to enable end-to-end command and data exchange between various components in WAN and LAN; there is still no clear standard for HAN [2].

Furthermore, to minimize the number of customers as well as DGs affected by faults and disturbances, a high-speed communication and an adaptive multi-criteria algorithm are required. The fast and reliable communication could monitor a small change in the grid configuration.

B. Technical Challenges in DC Microgrid

Although dc microgrids offer the different advantages, tendency for implementation of dc microgrids encounters a tough obstacle, which is protection of DC microgrids. Some of protection challenges such as microgrid operation modes, DERs impacts on PDs, standardization, and topology-

dependence PDs coordination are common between AC and DC microgrids. However, there are some additional challenges are required to be addressed. These challenges are expressed as follows (also see Fig. 2):

- 1) *Grounding*: The main purpose of grounding is to detect the ground fault. In order to design the grounding system, two contradictory requirements must be taken into account [26]:
 1. Minimize DC stray current.
 2. Maximize personnel safety by minimizing the common mode voltage.
 Consequently, designing an optimum grounding system is a tough challenge.
- 2) *No zero-crossing current*: In ac system, mechanical circuit breakers disconnect circuit when currents cross zero at every half-period; however, in dc system CBs there are no zero crossings. And hence, currents have to be forced to zero by additional means [27]. In addition, low dc impedances make dc fault levels very high.

III. CURRENT APPROACHES FOR PROTECTION OF AC AND DC MICROGRIDS

There are some approaches for improving the protection performance. These approaches categorized into three main general groups: adaptive protection, current limiting, and standardization of protection (see Fig. 2).

A. Solutions for AC Microgrid Protection

- ✓ *Adaptive protection*: After advent of microgrids, conventional overcurrent protection relays encounter selectivity and sensitivity issues due to different levels of fault during islanded and grid-connected modes. One of the promising solutions is adaptive protection technique. In [28], a simple adaptive protection using local information is proposed to overcome the challenges of overcurrent protection. The detection algorithm was utilized to change the trip characteristics. A system independent adaptive protection scheme is presented for a high penetration grid [29]. To provide adaptive relay setting a centralized acquisition system is used to send a command signal. However, the scheme will not work well for a system with low DG penetration. In [30], a hierarchical protection scheme is presented for Illinois Institute of Technology (IIT) microgrid. This scheme has the following characteristics:
 - 3) Sufficient fault currents in island mode.
 - 4) Differential protection schemes.
 - 5) Adaptive protection schemes.
 - 6) Communication-assisted relays.
 The simulation results for grid-connected and islanded modes demonstrated the effectiveness of the proposed scheme.

- ✓ *Current limiting*: One of the effective approaches to confine fault current is current limiting. This goal can be achieved through various ways.
- *Virtual impedance*: Many approaches are offering to control power electronic converters. Among linear control methods, virtual impedance gets higher attention to shape the desired dynamic of power converters [31]-[33]. The contributions of virtual impedance are power flow control [34]-[36], ancillary service i.e. fault ride through, [37]-[40], and harmonic compensations [41]-[43]. One of the proper approaches for limiting the current under the fault current is virtual impedance [37]-[40]. In this case, virtual impedance reduces the voltage reference to confine the current.
- *Fault current limiter*: According to the LVRT capability, DGs must have to connect to grid during the faulty condition. One of the existing solutions to stand against faults is fault current limiter (FCL) [44]-[45]. Location, optimal parameters of the FCL, and regarding coordination are crucial to improve the FLC performance.
- ✓ *Fault detection*: Fault or islanding detection could have a numerous contributions (i.e. facilitate applying adaptive protection and active management) to the grid [46]-[47]. Basically, islanding detection methods are classified into three main categories: active, passive, and communication-based approaches [46]. Unlike passive methods, active methods have nearly zero nondetection zone (NDZ). However, special attention must be paid to the current injected to the grid. One the other hand, communication-based islanding detection methods are reliable and no NDZ; but, high expensive to implement. Due the complexity of the future grid, communication system is widespread, and protection and control system must collaborate and communicate with each other. As a result, the promising islanding detection methods must meet the smart grid requirements.
- ✓ *Standardization*: To achieve the highly cooperative relationship of different components of the grid, standardizations for implementation of smart grids as well as a high reliable and cost-effective communication are required [48]-[49]. The international electrotechnical commission (IEC) Smart Grid Standardization Roadmap [50] suggests various core standards for the realization of the smart grids, categorized as follows: 1) IEC 61850 for power utility automation 2) IEC 61970/61968 Common Information Model (CIM) for energy and distribution management 3) IEC TR 62357 for service oriented architecture 4) IEC 62351 for security 5) IEC 62056 data exchange for meters, and 6) IEC 61508 for functional safety. IEC 61850 standard is particularly designed for information exchange between IEDs and modeling of

system's elements. Then after, IEC 61850-7-420 and 61850-90-7 standards were added to the primary IEC 61850 standard to develop exchanging information, power system modeling, and communication among DERs from different vendors [51]-[52]. However, one thing missed in the IEC 61850 standard is no standardization of sequential, combinational, rule-base (or any other forms) of power system control and automation logic such as interlocking logic for control operation [53].

The IEC 61499 standard is proposed to model distributed industrial-process measurement and control systems. The architecture of IEC 61499 standard is based on function blocks (FBs) encapsulating functionalities, behaviors, and their signal interconnection. These FBs could combine together to constitute a complex and hierarchical system description. The use of the FBs facilitates implementation of control system [53].

As inferred from previous parts of this paper, a proper protection scheme of AC and DC microgrids must consist of communication links, control system and intelligent management center. As a result, a promising standard must cover both communications, modeling and distributed control. The integration of IEC 61850 and IEC 61499 standards could meet the mentioned requirements [53]-[54]. Implementation of IEC 61850 logical nodes (LNs) and logical devices (LDs) is realized via IEC 61499 basic and composite FBs. Furthermore, IEC 61850/61499 can be used for the purposes of control functions and monitoring functions.

- ✓ *Self-healing actions:* Self-healing is an ability to allow resilience and fast recovery of the power system in response to the fault conditions have been envisioned. Self-healing usually refers to reconfiguration, load shedding, or controlling the dispatchable generators' output powers. Self-healing actions are a multi-objective, nonlinear optimization problem with couples of topological and operating constraints. Fuzzy system [55], multi-agent system (MAS) [56], and heuristic search [57] are sets of the main approaches to cope with complexity of restoration in distribution systems. However, restoration problems are much sophisticated in microgrids due to some challenges such as bidirectional power flows, mesh configuration topologies, and limited capacities of DERs. Recently, MAS and graph theoretic-based approaches were proposed for restoration in microgrids [58]-[59], whereas, these papers do not considers many issues (i.e. load priorities, stranded vertices and etc.)

B. Solutions for DC Microgrid Protection

Some of the solutions are common in AC and DC microgrids i.e. adaptive protection, standardization, and reconfiguration. However, other solutions such as DC fault

detection methods, optimal grounding systems, and current limiting approaches in DC microgrids.

- ✓ *Grounding systems and fault detection:* DC microgrid needs to be floating system. There are some reasons for high impedances grounding s follows:
 - Navy army is floating to guarantee continuity of energy to essential loads.
 - Some industrial system refuse to grounding system for not let an extra increase in common mode voltage. Due to the low ground current, detection of fault is difficult. Furthermore, second ground fault in another pole results in line-to-line fault causes a significant damage. As a result, detection in ungrounded system is a vital action toward improving ungrounded or even grounded system performance [60]-[61].
- ✓ *Current limiting methods:* Due to no zero-crossing current in DC microgrid, new approaches or physical circuit are necessary for DC microgrids. Some of the promising solutions are as follows:
 - *Z-source circuit breakers:* To avoid arc on the solid-state DC breaker (SSDCB), and axillary circuit switch as well as precharged commutation capacitor are employed to force commutate by reverse biasing. However, auxiliary solid state switching device must be actively driven to reverse bias before fault current exceed the interrupt capability of the breaker [62]. Hence, strict fault detection and timing is a critical issue for the conventional circuit breaker. Recently, creatively designed Z-source circuit breaker (ZSCB) promises to mitigate this problem [63]. The main idea of ZSCB is to take part of large transient fault current and force zero crossing zero in silicon circuit rectifier (SCR) by natural commutation. Then after, once the current in the SCR approaches zero, the SCR naturally switches off. In order to make ZSCB more practical the following three prominent shortcomings must be resolved:
 - I. ZSCB could not provide prolonged protection.
 - II. To be activated large transient fault is required.
 - III. No common ground or large fault current in generation sources.
 As a result, new topologies of ZSCBs have to be designed to eliminate the main drawbacks of the conventional ZSCBs.
 - *Virtual impedance:* Although there exists a few papers on limiting the current through virtual impedance [37]-[40], to the authors' knowledge virtual impedance approaches for limiting the current is at its infancy stage in DC microgrids. Thus further models and investigations are still required.

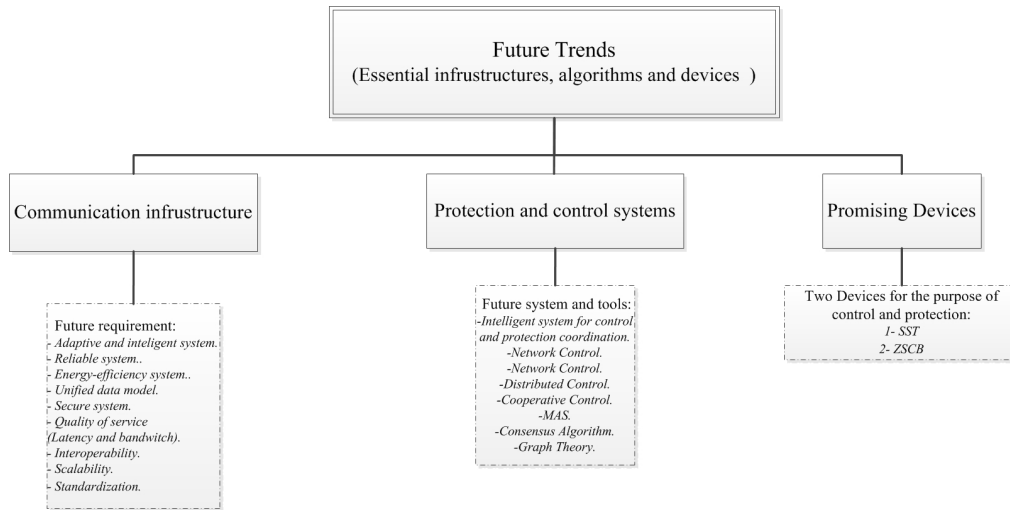


Fig. 3. Future trends for implementing microgrids including communication infrastructure, control and protection systems, and promising devices.

IV. NEW TRENDS AND OPEN ISSUES

According to the previous parts, AC and DC microgrids are confronting the minor or major protection challenges. Regarding the smart grid structure, an intelligent coordination of communication systems, control systems, and protection systems leads to a resilient and robust microgrids' structure. Consequently, from authors' viewpoint, different layers in the smart grid must be developed and reinforced to fundamentally address the current and upcoming challenges of microgrids protection. These three main parts are as follows (see Fig. 3):

A. Communication and information infrastructures:

The smart grid could roughly be divided into three domains in terms of communication coverage and functionality: home area network (WAN), neighborhood area network (NAN), and home area network (HAN). According to the each domain's characteristics, dedicated communication technology might be different for the each domain. For example, third generation (3G) and fourth generation (4G) cellular networks, worldwide interoperability for microwave access (WIMAX), cognitive radio technology, and optical networks are employed for WAN; whereas, power line communication (PLC), energy efficient Ethernet (EEE), visible light technology, Wi-Fi, and Zigbee are appropriate candidates for HAN. Regarding these technologies, a number of challenges are still required to be addressed [64]:

- Increase data rate by some advance technology such as high data rate long term evolution (LTE), LTE advanced (LTE-A), multi input multi output (MIMO); however, MIMO incur high energy consumption. Some remedies i.e. reducing the number of active antennas was proposed [65].
- Increase energy efficiency by Relaying techniques, mobile relay, cooperative communication, coordinated multi-point (CoMP) technology, sleep/wake-up schedule of base stations (BSs) in wireless network and optical network units (ONUs) in optical network. In addition some issues must be

taken into accounts such as quality of service (QoS), strict delay or delay-tolerant manner of smart grid, and smart grid traffic volume, and link speeds [64].

- Optimal communication network could be achieved by combining different technologies. Typically optical networks offer high speed, large bandwidth and high degree of reliability. On the other hand, wireless technologies have the characteristics of ubiquity, coverage and flexibility. Hence, optical-wireless network has all their benefits. However, energy-efficiency of this system is still challenging [64]. Recently, Fiber-wireless sensor networks (Fi-WSNs) are proposed for fast and reliable monitoring of indoor and outdoor facilities in smart grid [66].

As a consequence, besides operational limits of latency, pocket loss other issues such as energy-efficiency, optimality of communication network, reliability and flexibility of communication systems must also take into account.

One of the main obstacles for practical implementation of smart grids is the lacking of widely accepted standards. Although, standards are designed for various purposes such as system automation, AMI, HAN, electric vehicle, EMS etc; some shortages still remain in standards. For example, IEC 61850 only defines the unified information model for IEDs. There is a shortage of function algorithms; whereas, based on the concept of FBs, the unified function of IEDs is defined in the IEC 61499. Thus, it makes significant sense to integrate these two standards to establish standard FBs for flexible IEDs. Hence, the requirements of a system have to be determined, then based on its requirements a proper standard will be chosen. The proper standard could be original, modified or combinational of standards.

B. Control and protection systems:

In AC and DC microgrids, protection scheme must incorporate with control system, because of some issues such as LVRT capability, reconfiguration and self-healing, and approaching current to zero before CBs operations in DC microgrid. This integration is achieved under the well-

designed communication and information infrastructures; moreover, microgrids move toward distributed structure, thus other new control and communication concepts have to be considered to facilitate operation of control systems in distributed manner. These issues are multi-agent system (MAS), distributed control, network control, corporative control, consensus algorithms, and sparse communication.

C. Smart protective and control devices:

Recently, the solid-state transformer (SST) has been regarded as one of the 10 most emerging technologies by Massachusetts Institute of Technology (MIT) Technology Review in 2010, has gained increasing importance in the future power distribution system. The SST designed for the purposes of power flow control, voltage sag compensation, fault current limitation, seamless transition between the microgrids' two operation modes, isolation, active power management of the DC microgrids, and providing dc and ac interface. As a result, the SSTs are suitable candidates to improve the microgrids performance in term of energy transfer, protection and control. Although, significant progresses have been made in the SST technologies, the cost and reliability issues of the SST are the main issue that hampers it into the market. On the other hand in some applications such as aircraft and locomotive systems, the weight and size are more important than the cost [67].

One another technology used to cope with the problem of non-zero crossing current is the Z-source circuit breaker [62]-[63]. However, some of its drawbacks such no prolonged protection and no common grounding connections are required to be addressed.

V. CONCLUSION

Microgrid is considered as a main part of smart grid. Protection is the one of the most tough challenges in microgrids. Nevertheless, few papers have been concentrated on the protection of microgrids. On the other hand, to the authors' knowledge, no comprehensive paper have been published on the protection challenges and the possible solutions to address them in AC and DC microgrids. As a result, this paper fills this gap by presenting various challenges in AC and DC microgrids and addressing these challenges by several approaches. Finally, this paper investigates the future trends and their related open issues in order to pave the way of implementation of protection in microgrids.

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